Journal of Zhejiang University SCIENCE A
ISSN 1673-565X (Print); ISSN 1862-1775 (Online)
www.zju.edu.cn/jzus; www.springerlink.com
E-mail: jzus@zju.edu.cn

Studies of surface plasmon resonance sensor using bi-beam differential measurement approach*

ZENG Han-rong†, WANG Xiao-ping†‡, ZHANG Xue-jiao
(*Department of Optical Engineering, Zhejiang University, Hangzhou 310027, China*)
†E-mail: xxgczhr@yahoo.com.cn; xpwang@zju.edu.cn
Received Jan. 28, 2007; revision accepted June 6, 2007

Abstract: In this paper, a low-cost measurement approach with bi-beam was presented, which can be used for real-time detection and online analysis of solution refractive index, based on systematical analysis and experiments of conventional detection methods on surface plasmon resonance sensor. This novel method was analyzed theoretically and based on it a sensor system set was established. The factors that affect the sensor's sensitivity and working range were discussed. The angular adjustment setup was simplified, errors produced by movable components were avoided and the maneuverability was enhanced with this new method. The noiseproof feature and stability of the sensor system were greatly improved as well.

Key words: Kretschmann prism structure, Light intensity, Bi-beam measurement, Light differential, Surface plasmon resonance
doi:10.1631/jzus.2007.A2027 **Document code:** A **CLC number:** O43; O53

INTRODUCTION

With the advantages of label-free, fast response, high sensitivity and applicability for real-time detection, the surface plasmon resonance (SPR) sensor has achieved great development over the past decade. The technique has been applied in many fields such as biology, chemistry, environics, bromatology, medicine, pharmaceutics, etc. (Zhao *et al.*, 2000). There are four regular SPR detection methods: angle modulation (Kambhampati and Knoll, 1999; Esteban *et al.*, 2000; Kurihara and Suzuki, 2002), wavelength modulation (Slavik *et al.*, 1998; Toyama *et al.*, 2000; Bevenot *et al.*, 2002; Abdelmalek, 2002), light intensity modulation (Homola *et al.*, 1999; Ho *et al.*, 2001) and phase modulation (Nelson *et al.*, 1996). Angle modulation and wavelength modulation have higher resolution and sensitivity (the sensitivity can reach 10-7RIU), but they need a set of high accuracy tuning devices that have complicated structure, huge volume and high cost, which makes it inconvenient for field detection. Phase modulation has much higher detection sensitivity, but the same problems still exist and it is hard to realize portable sensor. Light intensity modulation features simple structure and low cost, however, due to bad sensitivity (10-5RIU) and weak anti-interference ability, its utility is limited.

How to improve the SPR sensors' detection sensitivity and resolution? How to optimize the sensors' structure? They have been hot research areas in SPR application for a long time. In this paper, a new measurement approach with bi-beam was presented and a set of sensor system based on it was established. Theoretical analysis and calculation indicated that the novel method enhances the sensor's sensitivity (higher than 10-5RIU) and resolution, the noiseproof feature and stability of the sensor system are greatly improved as well.

SENSOR STRUCTURE AND PRINCIPLE OF BI-BEAM DIFFERENTIAL MEASUREMENT

Fig.1 is a single-beam SPR sensor configuration

‡ Corresponding author
* Project supported by the Hi-Tech Research and Development Program (863) of China (No. 2006AA06Z406) and the Natural Science Foundation of Zhejiang Province (No. Z504009), China

based on Kretschmann prism structure (Cai *et al*., 1999). The main components include rectangular prism, metallic film and measured liquor. While p-polarized light is totally reflected, the electro-magnetic field component penetrates a short (tens of nanometers) distance into metallic film creating an exponentially attenuating evanescent wave, which induces the free electrons in the metal to produce a sharp shadow (SPR). When the evanescent wave and the surface plasmons wave have the same frequency and wave vector, resonance happens and the total reflection condition is ruined. Free electrons in the metal adsorb the incident light and attenuate the intensity of the reflected light rapidly. The specific incident angle that totally reduces the reflected light is called "resonance angle" (or SPR angle) (Jiang *et al*., 2003).

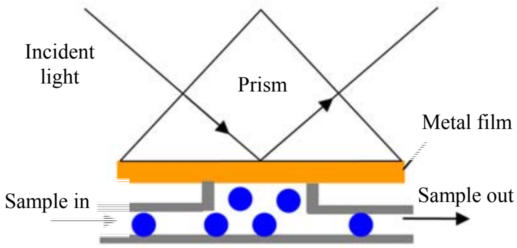

Fig.1 Single-beam surface plasmon resonance (SPR) sensor configuration

According to the relationship of frequency and wave vector between the evanescent wave and surface plasmons wave, the resonance angle can be expressed as:

$$\theta_{\mathrm{spr}} = \arcsin\left(\frac{\sqrt{\varepsilon_1'\varepsilon_2/(\varepsilon_1'+\varepsilon_2)}}{\sqrt{\varepsilon_0}}\right), \tag{1}$$

where ε_1' denotes the real part of the dielectric constant of the metal, ε_0 and ε_2 denote the dielectric constant of the prism and the measured liquor, respectively.

According to Maxwell equation and the boundary condition, if the incident light is p-polarized, the reflection index R is:

$$R = \left|\frac{r_{01} + r_{12}\exp(2\mathrm{j}k_{Z1}d)}{1 + r_{01}r_{12}\exp(2\mathrm{j}k_{Z1}d)}\right|^2, \tag{2}$$

where

$$r_{ij} = \frac{(\cos\theta_i)/\tilde{n}_i - (\cos\theta_j)/\tilde{n}_j}{(\cos\theta_i)/\tilde{n}_i + (\cos\theta_j)/\tilde{n}_j},\ (i, j=0, 1, 2) \tag{3}$$

$$n_0\sin\theta_0 = \tilde{n}_1\sin\theta_1 = \tilde{n}_2\sin\theta_2,$$

$$\cos\theta_i = (1-\tilde{n}_0^2\sin^2\theta_0/\tilde{n}_i^2)^{1/2},$$

where subscripts 0, 1, 2 denote the prism, the metallic film and the measured liquor respectively, k denotes the wave number and θ_i denotes incident angle at different interfaces. SPR results from excited surface plasmon waves that prograte at the interface between the metal and the medium. The excitation condition is decided by the dielectric constant of the metal ε_1' and the medium ε_2, the thickness of the metallic film d, the wavelength λ and the incident angle of the incident light θ_0. According to Eqs.(2) and (3), it can be easily concluded that the intensity of the reflected light p is only determined by the measured liquor's refractive index $\tilde{n}_2$, provided that ε_1', ε_2, d, λ and θ_0 are all constant. $\tilde{n}_2$ can be obtained by just detecting p. However, in the actual sensor system, change in p is induced by many factors such as the fluctuation of the light source, the variation of the ambient conditions and the sensor vibration. The change will weaken the stability and the noiseproof feature of the light intensity modulation sensor, and then greatly limit the application. Besides, the SPR curve of intensity vs. refractive index is a quadratic curve (see Fig.2), that is to say, one reflected light intensity has two corresponding refractive indexes. The range of the refractive index of the sample has to be foreseen to

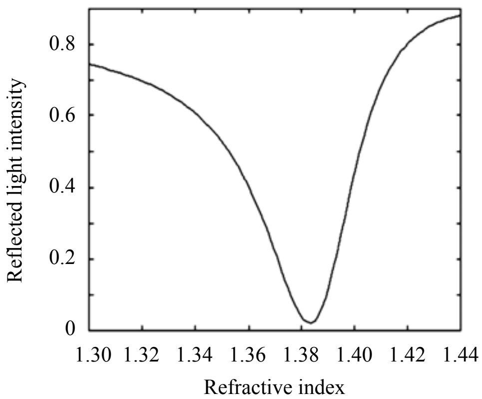

Fig.2 Dependency of the reflected light intensity vs. the sample refractive index when using a single beam. λ=632.8 nm, ε=−9.9687+0.8216j, θ_0=57°

realize accurate measure, which definitely makes it more difficult to the application. In order to improve the stability and the noiseproof feature of the light intensity modulation sensor, and extend the detection range, a differential measurement approach with bi-beam was proposed in this article.

Fig.3 shows the model of SPR sensor system using bi-beam. Two p-polarized light beams Beam 1 and Beam 2 are transmitted on the prism surface at different angles. The intensities of the reflected light $p(\theta_1)$, $p(\theta_2)$ are detected by the electrophotonic detectors PD1, PD2, respectively. The difference of the two light intensities can be defined as $\Delta P=P_{11}-P_{12}=P_{01}R_1-P_{02}R_2$, where P_{01} and P_{02} denote the intensity of the incident light of Beam 1 and Beam 2 respectively, R_1 and R_2 denote the refractive index of Beam 1 and Beam 2 respectively. Suppose the two incident beams have the same intensity (i.e., $P_{01}=P_{02}=P_0$), then $\Delta P=P_0(R_1-R_2)$. The difference of the reflected light intensity is only determined by the difference of the reflection indexes. When the two incident angles are 57° and 62°, two SPR curves appear as Fig.4a shows. Further calculation gives the relationship between the difference of the reflected light intensity and the refractive index using bi-beam, as Fig.4b shows.

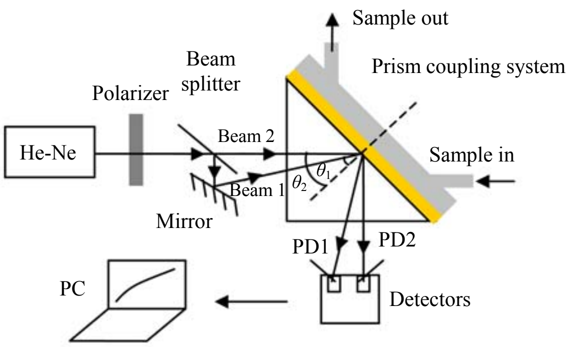

Fig.3 Surface plasmon resonance (SPR) sensor system using bi-beam

In light intensity modulation, sensitivity can be defined as the light intensity variation corresponding to unity refractive index variation. The same definition can be used in bi-beam differential measurement approach. According to Fig.4a, when the incident angle is 57° and the refractive index is within 1.382~1.420, the SPR curve has the best sensitivity and linearity. And according to Fig.4b,

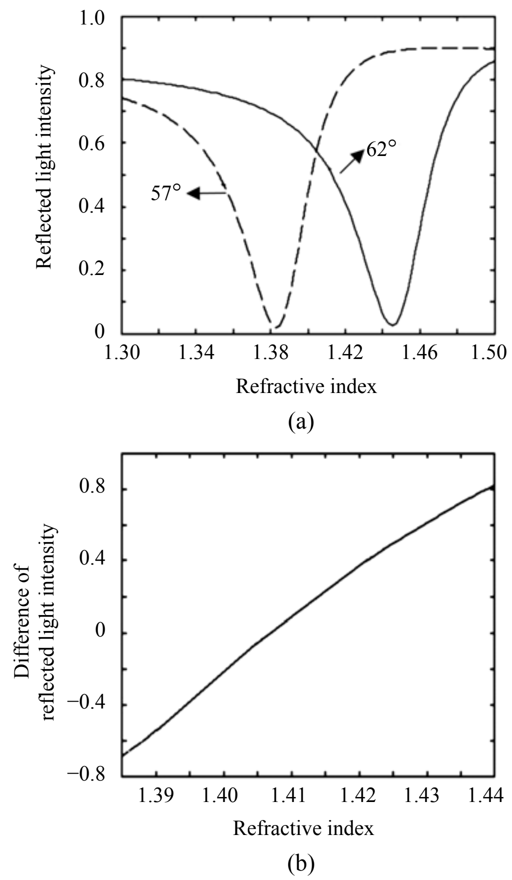

Fig.4 (a) Two SPR curves at different incident angles; (b) Dependency of the reflected light intensity difference vs. the sample refractive index when using bi-beam

when the refractive index is within 1.382~1.440, the relationship curve of the reflected light intensity difference vs. the refractive index of the sample has the best linearity. The span of the light intensity difference is also enlarged (+0.82~−0.68), twice that of the single SPR curve (0.88~0.02). So it can be concluded that the bi-beam differential measurement approach has higher sensitivity and wider detection range compared to the traditional approach.

This bi-beam SPR measurement approach keeps the merit of simple structure in the light intensity modulation sensor. And because of using the differential measurement approach at the same time, it limits well the fluctuation of the light source, the variation of the ambient conditions and many other interfering factors. The noiseproof feature and stability of the sensor system are greatly improved as well.

NUMERICAL SIMULATION OF SPR SENSOR USING BI-BEAM

Relationship between detection range and incident angle

In order to improve the detection sensitivity of the sensor and widen the detection range, it is very important to choose a suitable incident angle. Although SPR can be produced when the incident angle is bigger than the critical angle, the intensity of the p-polarized beam will vary intensively only around the resonance angle. So in the bi-beam measurement, the incident angle of the two lights must be chosen close to the resonance angle.

The results of the theoretical analysis, the numerical simulation and emulator indicate that when the difference of the two lights' incident angles equals 5°, the bi-beam measurement approach has higher sensitivity and wider detection range. Fig.5 shows the relationship curve of reflected light intensity vs. the refractive index of the sample at different angles.

As Fig.5 shows, if the incident angle varies, the detection range varies as well. When the incident angle is 52°, the detection range of the corresponding refractive index is 1.310~1.382; when the incident angle is 57°, the detection range of the corresponding refractive index is 1.382~1.445. Using the characteristic, by rotating the sensor 1°/step, different samples in different refractive index extensions can be detected. So this bi-beam measurement approach omits the angular adjustment setup that must be used in the traditional light intensity modulation approach, lowering the cost and complexity of the system.

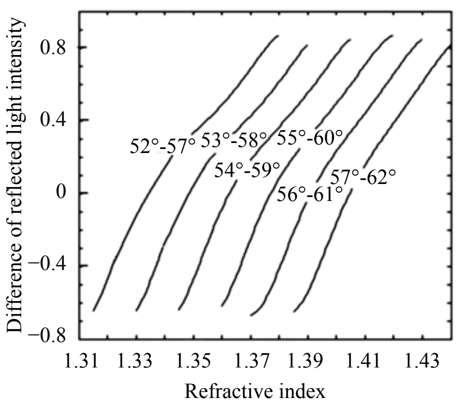

Fig.5 Dependency of the reflected light intensity vs. the sample refractive index at different angles (incident angle difference of the two lights $\Delta\theta_0$ equals 5°)

Relationship between detection sensitivity and metallic film material and thickness

In the bi-beam measurement approach, there are many factors influencing the sensitivity of SPR sensor. One of the important factors is the metallic film which produces surface plasmon wave. The optical parameters of the metallic film (material and thickness) will directly affect the detection sensitivity of the sensor.

Ag- and Au-film are mostly used in SPR sensors. Now there is also a new kind of Ag/Au metallic film which combines the high detection sensitivity but easily oxidized features of Ag-film and good stability but bad adhesiveness features of Au-film. For example, 47 nm Ag-film is sputtered on the bottom of the SPR sensor by the magnetic controller, and another 5 nm Au-film is sputtered over it equably. Then a 47 nm (Ag)/5 nm (Au) combined metallic film (Sharma and Gupta, 2006) is formed, which can be used to optimize the sensor performance.

The thickness of metallic film is an important factor which affects resonance depth. Since the resonance depth of the evanescent wave is about wavelength level, too thick metallic film diminishes the evanescent wave of penetrating the membranous layer and reaching the sample; whereas too thin metallic film leads to invisible SPR effect. The phenomenon can be explained well from the electromagnetic field theory. Usually the thickness of the metallic film is less than 100 nm (Weiss *et al*., 1996).

If a reasonable thickness of metallic film is chosen via theoretical calculation, the approximate expression of reflectivity R can be inferred according to Eq.(2) when the incident angle is close to the resonance angle. Obviously, the deeper the SPR resonance is, namely the smaller the reflectivity R is, the higher is the sensitivity. So according to R_{min}, the thickness of the metallic film d can be figured out. In order to minimize the error, take the parameters we already have as the reference, use Matlab and the least squares techniques to optimize the parameters, making sure that the error of resonance angle is less than 0.005°, then a reasonable thickness of the metallic film (Yue *et al*., 2001) can be figured out.

In this paper, Au-film was taken as an example to illustrate the relationship between the thickness of the metallic film and the sensitivity of the SPR sensor.

Fig.6 is obtained using Matlab. It demonstrates the dependency of the refractive index of the sample vs. the reflected light intensity using different Au-film with thickness of 20~60 nm. Here, sensitivity can be defined as light intensity variation corresponding to the unity refractive index variation, namely the slope of the curve in Fig.6. As Fig.6 shows, when the thickness of Au-film is about 40~50 nm, the sensitivity of the sensor is higher. Out of the range, the sensitivity will become lower and the linearity will get worse as well.

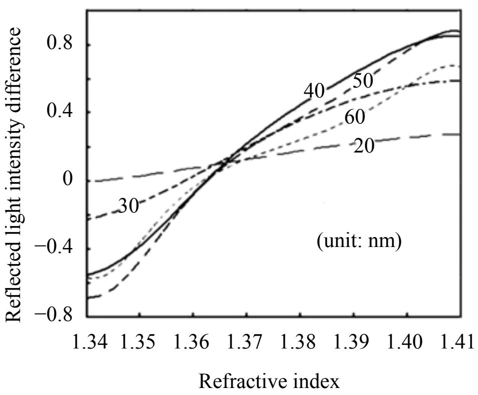

Fig.6 Dependency of the refractive index of sample vs. the reflected light intensity when using different Au-films. λ=632.8 nm, ε_0=3.24, ε_1=−13.4+1.4j

CONCLUSION

The SPR bi-beam measurement approach we presented here keeps the characteristic of SPR sensor. And since bi-beam SPR sensors do not need to scan the incident angle precisely, the angular adjustment setup is simplified, the giant structure and complicated system in traditional approach are avoided, and the maneuverability is enhanced. The application of light difference also improves the stability, noise-proof feature and reliability of the sensor system. Optoelectronic diode can be used instead of optical spectrometer or expensive CCD array because only the two beams' light intensity signals need to be detected. So the system complexity and factory cost can be greatly reduced, and it is easier to be designed as a portable instrument.

References

Abdelmalek, F., 2002. Surface plasmon resonance based on Bragg gratings to test the durability of Au-Al films. *Mater. Lett.*, **57**:213-218. [doi:10.1016/S0167-577X(02)00767-X]

Bevenot, X., Trouillet, A., Veillas, C., Gagnaire, H., 2002. Surface plasmon resonance hydrogen sensor using an optical fiber. *Meas. Sci. Tech.*, **13**:118-124. [doi:10.1088/0957-0233/13/1/315]

Cai, Q., Li, X., Chen, Y.Q., 1999. The history, actuality and prospect of surface plasmon resonance biosensor. *Foreign Med. Sci. (Biomed. Eng. Fascicle)*, **22**(2):65-71 (in Chinese).

Esteban, O., Navarrete, M.C., Gonzalez-Cano, A., 2000. Simple model of compound waveguide structures used as optic sensors. *Optics & Lasers in Eng.*, **33**:219-230. [doi:10.1016/S0143-8166(00)00040-3]

Ho, H.P., Wu, S.Y., Yang, M., Cheung, A.C., 2001. Application of white light-emitting diode to surface plasmon resonance sensors. *Sensors and Actuators B*, **80**:89-94. [doi:10.1016/S0925-4005(01)00881-4]

Homola, J., Yee, S.S., Gauglitz, G., 1999. Surface plasmon resonance sensors: review. *Sensors and Acuators B*, **54**(1-2):3-15. [doi:10.1016/S0925-4005(98)00321-9]

Jiang, X.M., Chen, Z.C., Yang, S.M., 2003. Progress of fiber optic sensor based on surfce plasmon resonance. *Chin. J. Sensors and Actuators*, **1**:74-75 (in Chinese).

Kambhampati, D.K., Knoll, W., 1999. Surface-plasmon optical techniques. *Current Opinion in Colloid & Interface Sci.*, **4**:273-280. [doi:10.1016/S1359-0294(99)90008-0]

Kurihara, K., Suzuki, K., 2002. Theoretical understanding of an absorption-based surface plasmon resonance sensor based on Kretchmann's theory. *Anal. Chem.*, **74**:696-701. [doi:10.1021/ac010820+]

Nelson, S.G., Johnston, K.S., Yee, S.S., 1996. High sensitivity surface plasmon resonance sensor based on phase detection. *Sensors and Actuators B*, **35**(1-3):187-191. [doi:10.1016/S0925-4005(97)80052-4]

Sharma, A.K., Gupta, B.D., 2006. Fibre-optic sensor based on surface plasmon resonance with Ag-Au alloy nanoparticle films. *Nanotechnology*, **17**:124-131. [doi:10.1088/0957-4484/17/1/020]

Slavik, R., Homola, J., Tyroky, J., 1998. Miniaturization of fiber optic surface plasmon resonance sensor. *Sensors and Actuators B*, **51**:311-315. [doi:10.1016/S0925-4005(98)00205-6]

Toyama, S., Doumae, N., Shoji, A., Lkariyama, Y., 2000. Design and fabrication of a waveguide-couple prism device for surface plasmon resonance sensor. *Sensors and Actuators B*, **65**:32-34. [doi:10.1016/S0925-4005(99)00427-X]

Weiss, M.N., Srivastava, R., Groger, H., Lo, P., Luo, S.F., 1996. A theoretical investigation of environmental monitoring using surface plasmon resonance waveguide sensors. *Sensors and Actuators A*, **51**:211-217. [doi:10.1016/0924-4247(95)01208-7]

Yue, P., Gu, Y.Q., Gu, J.H., 2001. The decision and application for SPR sensor's optical parameters. *Chin. J. Med. Phys.*, **18**(2):61-62, 65 (in Chinese).

Zhao, X.J., Chen, H.W., Song, D.Q., 2000. Surface plasmon resonance sensor 1: the basic principle. *Analytic Instrument*, **17**(4):1-8 (in Chinese).